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**Mars Polar Lander Thruster Cold Start  
Validation Testing**

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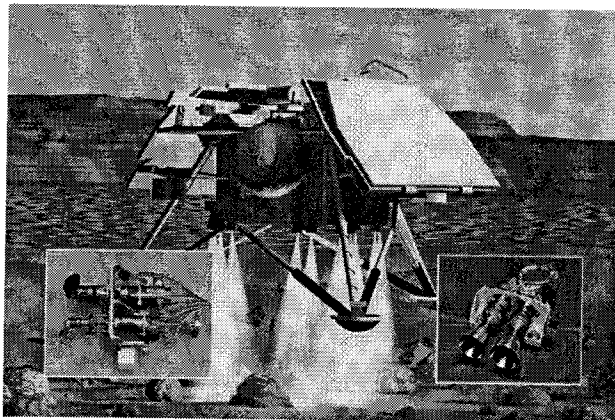
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### **Abstract**

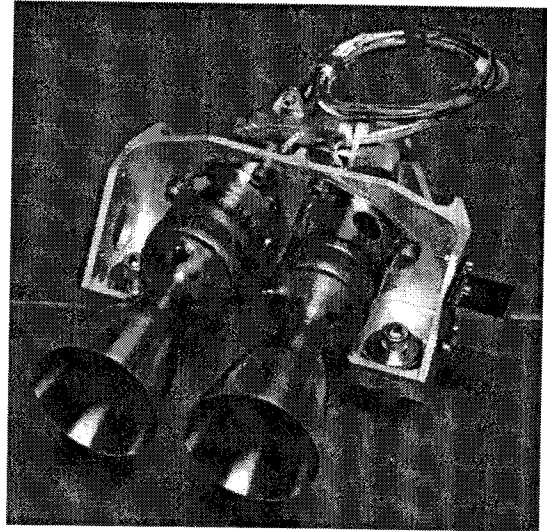
The Mars Polar Lander (MPL) Spacecraft used catalytic hydrazine thrusters to control its terminal descent onto the Martian surface. After the failure of the Mars Climate Orbiter Spacecraft in September 1999, the design of the MPL Spacecraft was extensively re-evaluated. As a part of that review, concerns were raised about the operation of the descent thrusters with catalyst bed temperatures from 0° C to minus 30° C. Testing conducted at General Dynamics (GD) Space Propulsion Systems (Previously PRIMEX Aerospace, Olin Aerospace and known to many as Rocket Research) in October and November of 1999 verified that the thruster could indeed be fired with catalyst bed temperatures as low as minus 28°C.

### **Introduction**

MPL was part of NASA's Mars Surveyor Program, to return to Mars and soft land on the south pole. The program was planned and executed under the challenges of the "Better /Faster /Cheaper" approach. Use of existing qualified designs, with supporting analysis and qualification by similarity, was a key method of achieving the program objectives. The MR-107N Rocket Engine Assembly (descent thruster), used to control the MPL terminal descent onto the Martian surface, was one such example. Figure 1 shows an artist's rendition of the MPL's twelve descent thrusters firing during final descent. The twelve thrusters were configured as Rocket Engine Modules (REM), shown in Figure 2. GD manufactured the thrusters (and REMs) as a modified version of a previously flight-proven design. The modifications included a slight increase in thrust level and were well within the experience base of GD.



**Figure 1 Artist's Rendition of Mars Landing**



**Figure 2 Rocket Engine Module for MPL**

One unique aspect of the MPL application was possible operation at very low catalyst bed temperatures. During cruise from Earth to Mars the thrusters were enclosed within an aeroshell and isolated from the propellant tanks with normally closed pyrovalves. During this time the propellant lines were evacuated and the thruster valves were not thermally conditioned. At 20 minutes prior to use the valve heaters were to be turned on to preheat the valves, followed by firing the pyro isolation valves to fill the manifold. The 12 flight descent thrusters were first used during the Mars landing sequence to perform a 2.5 second lander tip-up maneuver. During this maneuver, the thrusters were commanded at 10 Hz frequency with a nominal 30% +/-10% duty cycle (30 ms +/- 10 ms on time).

The rationale for not testing the thrusters at the low temperatures expected during cruise, was the previous experience at GD with the operation of similar thrusters at temperatures as low as minus 34°C. It was concluded, based on this previous experience, that the thrusters could be qualified by "similarity". This type of evaluation was inherent in "Better/Faster/Cheaper" programs. The issues surrounding "cold thruster" temperatures were revisited in considerable detail following the loss of the Mars Climate Orbiter (MCO), as discussed below.

After the failure of the MCO Spacecraft in September 1999, the design of the MPL Spacecraft was extensively re-evaluated. As a part of that review, concerns were raised about the operation of the descent thrusters with catalyst bed temperatures near minus 30°C. Since the MPL was already in cruise to Mars for an anticipated December entry and landing,

potential solutions were limited. It was decided that additional testing was warranted to validate the thermal predictions and assure the thruster capability. Testing conducted at GD in October and November, 1999 verified that the thruster could indeed be started with catalyst bed temperatures down to minus 28°C. It should be noted that the valve warm-up time was increased resulting in a nominal catalyst bed temperature of 12.8° C, providing significant margin above the cold start capability demonstrated.

### Test Overview

The thruster cold start test program consisted of two phases, each with two parts. The first phase consisted of thermal vacuum testing to measure the thruster and structure thermal characteristics and hot fire testing to determine minimum acceptable cold start catalyst bed temperature. The second phase consisted of additional thermal vacuum testing to further validate thermal modeling predictions using a high fidelity flight REM simulation (This data was used to update worst-case flight predictions) and a hot fire test series to verify thruster performance. The hot fire tests were at the nominal and worse case cold temperatures predicted during the first part of phase 2 testing. The results of the thermal vacuum tests are not discussed in this paper.

### Cold Start Test Plan

The test plan included the test conditions listed in Table 1 and Table 2. The temperatures in Table 2 were established from phase 2, part 1 testing. The hot fire test plan was designed in accordance with the "Test Like You Fly" philosophy to simulate actual flight conditioning. To protect the test article, the cold start demonstration (margin) testing used the following procedure:

- 1) Established enclosure temperature and cold plate temperature as required to condition thruster cat bed and valve below required test conditions. Turned on manifold and valve heaters to heat the propellant circuit to the test point conditions while maintaining catalyst bed temperature at or below the test point conditions.
- 2) Once the valve reached proper temperature it was evacuated and filled hydrazine to the thruster valve. The valve and line heater power was held until the propellant temperature was within test limits.
- 3) The valve heaters were turned off and test performed. Minimum cold start temperature tests were stopped after two pulses if chamber pressure rise had not occurred and the cat bed temperature was increased by 5° C and the test sequence repeated until successful. If chamber pressure rise occurred the test was continued for the remaining eight pulses.

### Test Setup

The test setup for hot fire and thermal vacuum included a large vacuum chamber with roughing and blower pumps, a cryo-pump for high vacuum testing, a thermal conditioning chamber with LN<sub>2</sub> coils, thermocouples, and a automatic thermal temperature controller.

The hydrazine supply system is shown schematically in Figure 3 and includes supply tanks with a helium pressurization system, filter, isolation valves, and drain/purge valves for system decontamination. The facility propellant lines were modified (diameters increased and lengths shortened) after test point 13 to reduce the pressure drop during the initial firing surge flow.

Table 1  
Test Plan Matrix  
(Including Minimum Start Capability)

Test Purpose	Cat Bed (°C)	Valve (°C)	Manifold (°C)	Fuel (°C)	Tank Press. (psia)	Duty Cycle (DC) (Control Freq. = 10 hz)
Min.	-25 to -30	> 2	> 2	10 +/- 5	450 +/- 5	20%, 2 + 8 pulses
Min.	-25 to -30	> 2	> 2	10 +/- 5	450 +/- 5	40%, 2 + 8 pulses
Margin	-15 to -20	> 2	> 2	10 +/- 5	450 +/- 5	40%, 25 pulses (Max DC)
Margin	-15 to -20	> 2	> 2	10 +/- 5	450 +/- 5	20%, 25 pulses (Min DC)
Margin	-15 to -20	> 2	> 2	10 +/- 5	450 +/- 5	30%, 25 pulses (Nom DC)
Checkout	Existing	Existing	Existing	Existing	450 +/- 5	2 sec. Steadystate

Table 2  
Flight Verification Cold Start Test Conditions

Test Purpose	Cat Bed (°C)	Valve (°C)	Manifold (°C)	Tank Press. (psia)	Duty Cycle (DC) (Control Freq. = 10 Hz)
Nominal	13	58	> 2	450 +/- 5	30%, 25 pulses
Worst Case Cold	- 5	50	> 0	450 +/- 5	30%, 25 pulses

The REM was mounted to a large aluminum plate/heat sink which used LN<sub>2</sub> coolant for temperature control, this system was manually controlled throughout all testing to maintain the REM interface temperature. A schematic of the REM with thermocouple locations is shown on Figure 4. Photographs of the REM, thruster, feedline, multi layer insulation and thermal control enclosure are shown in Figures 5, 6 and 7. Line heaters, thermocouples, and insulation were added to all propellant lines inside the thermal shroud to prevent hydrazine freezing.

Typical instrumentation included the parameters listed below.

- Temperatures: Relevant locations are shown in Figure 4.
- Pressure: Hydrazine Run Tank Pressure (P), Feed 1 (Pf1), Feed 2 (Pf2), Thrust Chamber (Pc), Test Cell Vacuum
- Power: Mount Plate Voltage and Current, Heater Valve A Voltage, Heater Valve B Voltage, Valve Coil A Voltage.

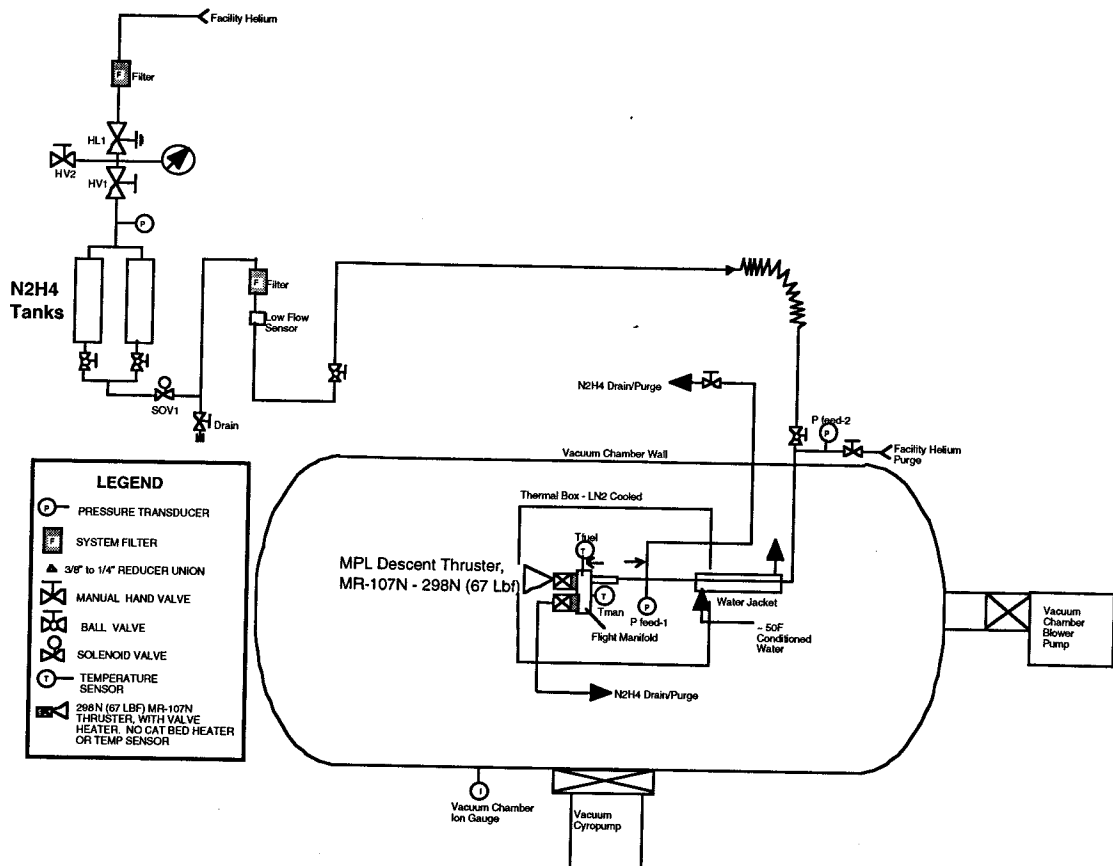
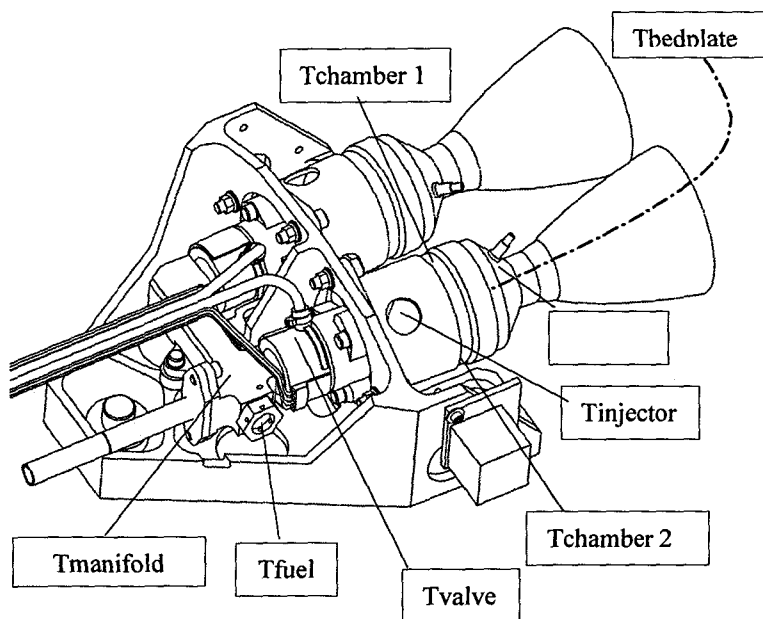
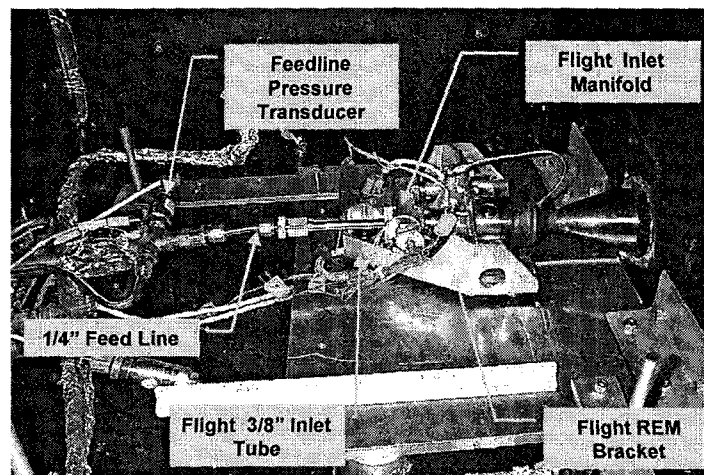


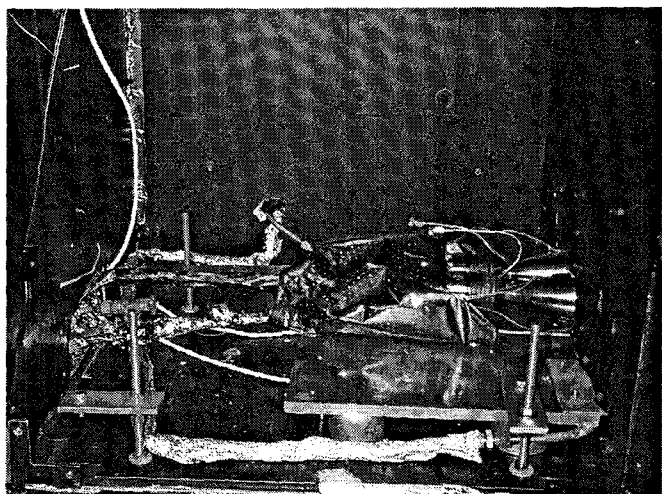
Figure 3 MPL Descent Engine Cold Start Test Schematic



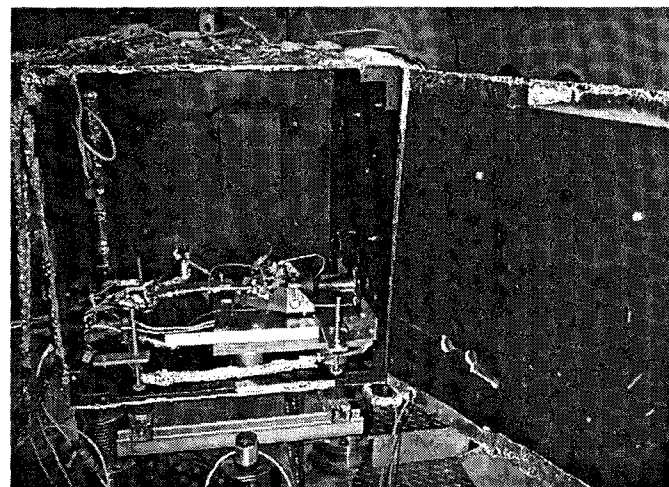
**Figure 4 . MPL Descent Engine REM  
with Thermocouple Locations**



**Figure 5 MPL Descent Engine  
REM- Test Setup**



**Figure 6 MPL Descent Engine REM with MLI  
- Test Setup**



**Figure 7 Thermal Enclosure Test Setup**

### Test Hardware

The flight configuration of the MPL REM was shown previously as Figure 2. Testing included two REM configurations, one with two thrusters as shown in Figure 6, and a configuration with a purge adapter in place of one thruster as shown in Figure 5. The purge adapter allowed evacuation of the hydrazine to prevent freezing of the fuel during test sequencing. This also allowed verification of the REM warm-up prior to firing the pyro isolation valves. The thruster used for all the firing tests was used previously for performance demonstration testing and for system water hammer testing at Lockheed Martin. Consequently, the thruster had accumulated over twice the required mission life. (3,149 pulses and 722 seconds of total firing time before cold start testing). This amount of firing would cause some reduction in catalyst activity and voiding in the catalyst bed. Consequently, the test was conservative compared to using a "new" thruster.

### Test Results

The test series included a total of 19 runs (Table 3) of which seven runs were with the catalyst bed between minus 30° C and 0° C. Tables 4 and 5 summarize the start temperatures of the seven "cold start" test runs. Test Points 18 and 19 represent the final predicted

nominal and worst-case cold mission conditions for the MPL.

The test success criteria was to achieve 80% nominal warm chamber pressure (pulse width dependent) within 10 pulses, and for no single pulse to be in excess of 125% warm nominal chamber pressure (pulse width dependent). Success criteria for 25 pulses was achieving 100% nominal warm chamber pressure (pulse width dependent) and no single pulse in excess of 125% warm nominal chamber pressure (pulse width dependent). This criteria was established based on the mission descent control requirements. Figures 8 and 9 show that the chamber pressure and impulse bit performance requirements were met for the cold start tests. The data shown in these figures are normalized by pulse width. As shown in Figures 8 and 9, catalyst bed start temperature does have an effect on I-bit and chamber pressure magnitude during the first 20 and 18 pulses respectively. Peak chamber pressures for the minus 20°C start temperatures were consistently lower during the start transient (first 18 pulses) than for the ambient (10°C to 20°C) starts. I-Bit data for minus 20°C start temperatures indicates an overshoot trend during the first three pulses.

Table 3 -Overall Cold Start Demonstration Hot Fire Test Matrix

Test Point(TP)	Duty Cycle (10 Hz)	Pulses	Valve Temp. (°C)	Manifold Temp. (°C)	Fuel Temp. (°C)	Cat Bed Temp.* (°C)
1	20 / 80	2, then 8	10	8	7	-26
2	40 / 60	2, then 8	11	8	8	-28
3	40 / 60	25	-	-	-	Existing (Hot)
4	20 / 80	25	-	-	-	Existing (Hot)
5	20 / 80	20	15	15	15	15
6	40 / 60	25	-	-	-	Existing (Hot)
7	20 / 80	25	-	-	-	Existing (Hot)
8	2 sec S/S	1	-	-	-	Existing (Hot)
9	40 / 60	2, then 8	8	11	10	-20
10	40 / 60	25	10	15	14	-19
11	20 / 80	25	11	10	9	-20
12	30 / 70	25	9	9	8	-19
13	2 sec S/S	1	-	-	-	Existing (Hot)
14	30 / 70	25	22	22	22	22
15	20 / 80	25	-	-	-	Existing (Hot)
16	40 / 60	25	-	-	-	Existing (Hot)
17	2 sec S/S	1	-	-	-	Existing (Hot)
18	30 / 70	25	56	24	22	12
19	30 / 70	25	31	11	12	-6

\* T<sub>average</sub> is average of T<sub>injector</sub>, T<sub>chamber1</sub>, and T<sub>chamber2</sub>

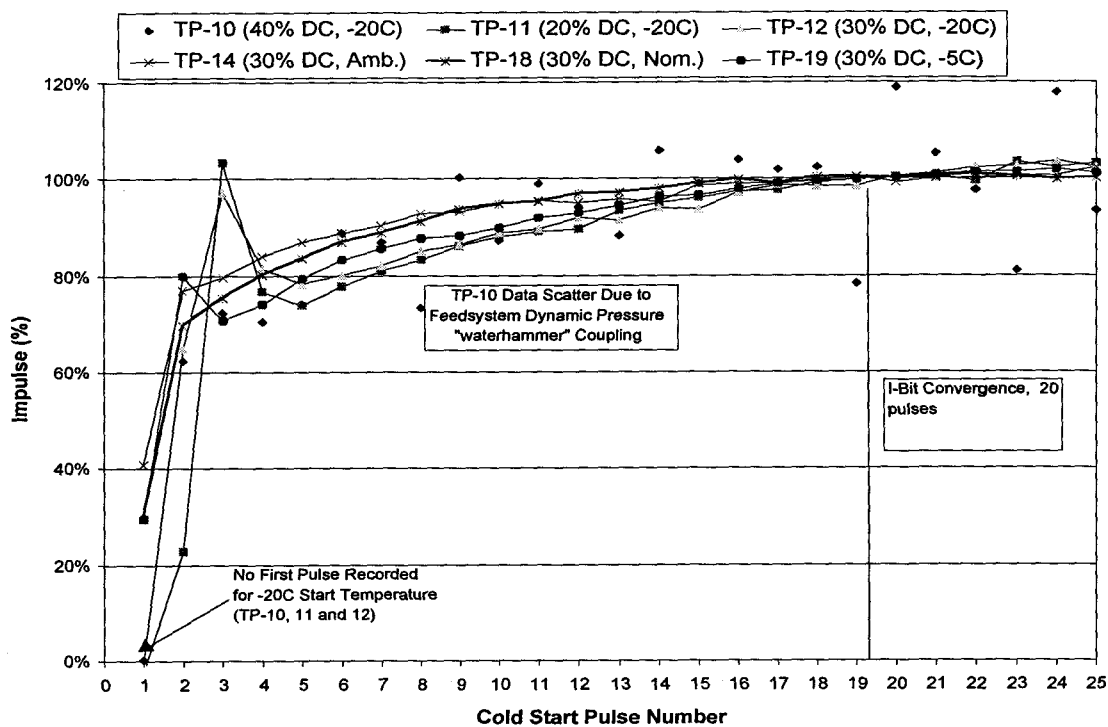
Table 4  
Cold Start Test Results

Test Point (TP)	No. Pulses Commanded	Pulses with measurable I-bit **	Pulse Width (sec)	Off Time (sec)	T <sub>average</sub> * (°C)
1	10	10	0.020	0.080	-26
2	10	9	0.040	0.060	-28
9	10	10	0.040	0.060	-20
10	25	24	0.040	0.060	-19
11	25	23	0.020	0.080	-20
12	25	24	0.030	0.070	-19
19	25	25	0.030	0.070	-6

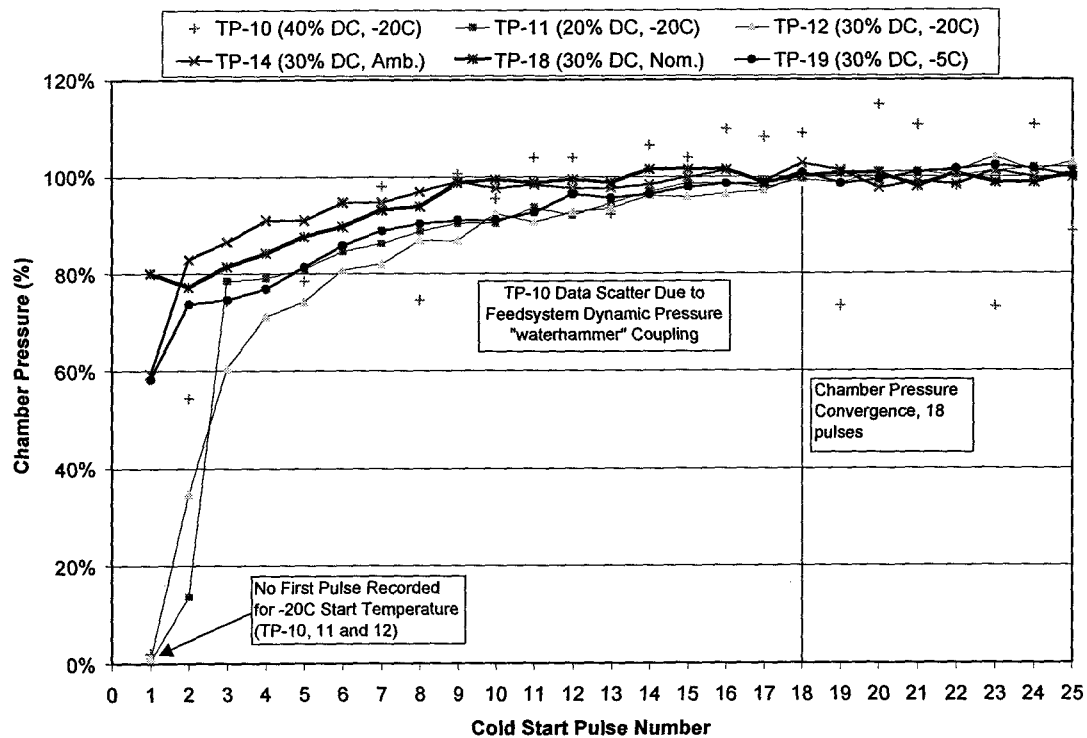
\* T<sub>average</sub> is average of T<sub>injector</sub>, T<sub>chamber1</sub>, and T<sub>chamber2</sub>

Table 5  
Cold Start Test Results (con't)

Run	T <sub>fuel</sub> (°C)	T <sub>injector</sub> (°C)	T <sub>chamber1</sub> (°C)	T <sub>chamber2</sub> (°C)	T <sub>bedplate</sub> (°C)	T <sub>throat</sub> (°C)
1	7	-25	-26	-28	-24	-34
2	8	-28	-28	-29	-24	-36
9	10	-22	-21	-18	-21	-28
10	14	-22	-20	-17	N/A	-27
11	9	-22	-20	-18	N/A	-28
12	8	-21	-20	-18	N/A	-27
19	12	-3	-8	-6	N/A	-13



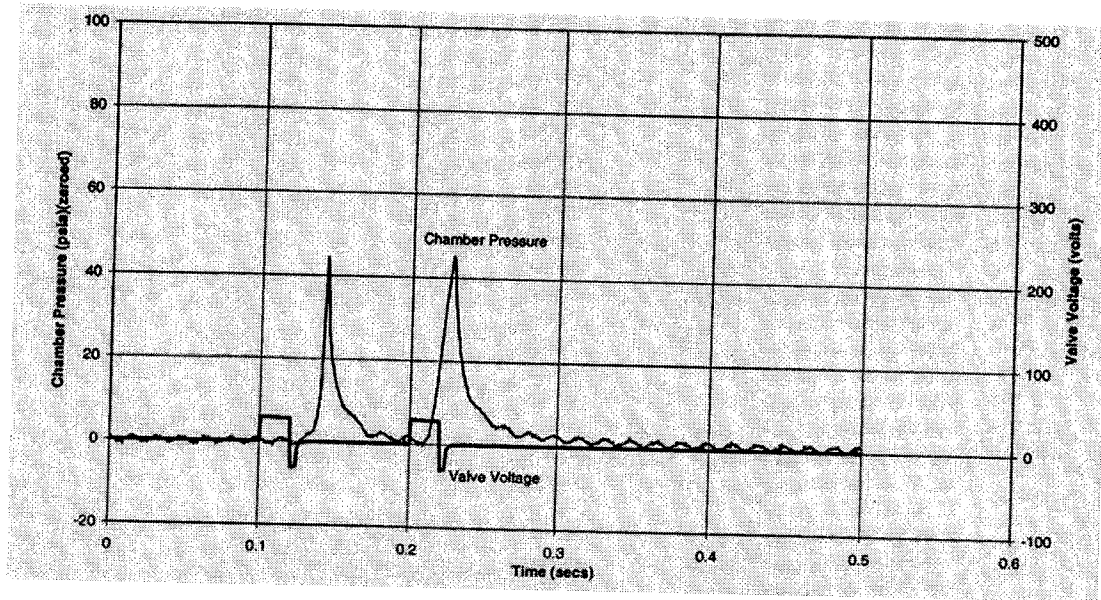
**Figure 8 I-Bit Cold Start Transient**



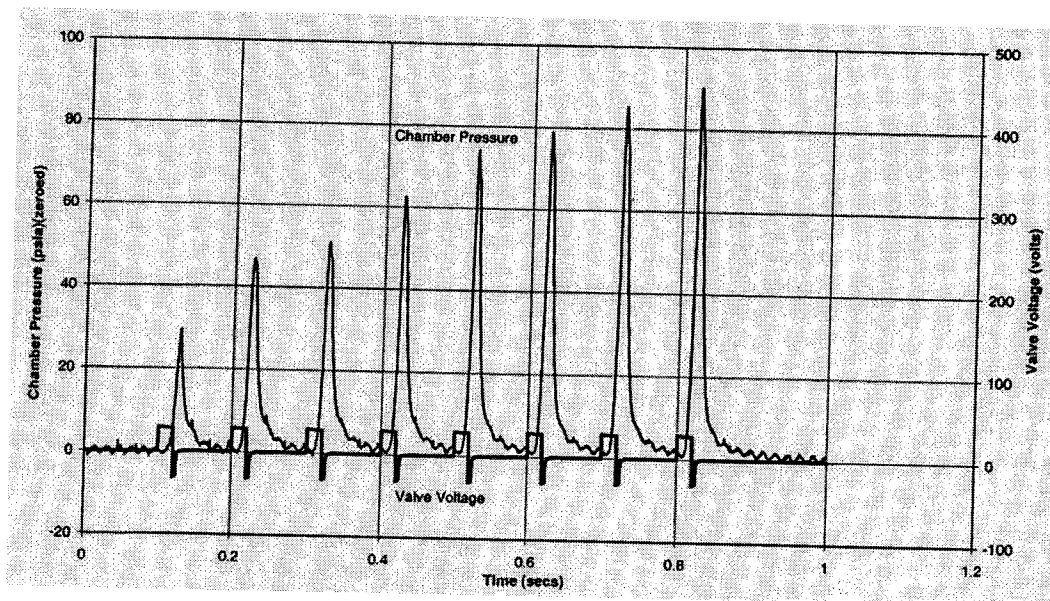
**Figure 9 Chamber Pressure Cold Start Transient**

At these very cold temperatures the first few pulses can have either significant ignition delays or no measurable impulse. In fact, the first one or two pulses might be mostly raw hydrazine passing through the catalyst bed largely undecomposed, as was evident on video as a "frost cloud" emanating from the thruster. Figure 10 shows the first two pulses of test point #1 and Figure 11 shows the following eight pulses. There was a programmed delay between the first two pulses and the remaining eight as a precautionary measure on the initial runs to preclude

the potential for large accumulations of frozen hydrazine in the catalyst bed. As listed in Table 4 all pulses were present for test run #1. Figure 12 and Figure 13 show pulses one through twelve and pulses thirteen through 25 respectively for test point #12. This is an example of a missing first pulse. In comparison, Figures 14 and 15 show pulses one thru twelve and pulses thirteen through 25 for the nominal predicted start temperature in test point #12.



**Figure 10 Test Point 1 (20% DC, -20C) Pulses 1 and 2**



**Figure 11 Test Point 1 (20% DC, -25C) Pulses 3 through 10**

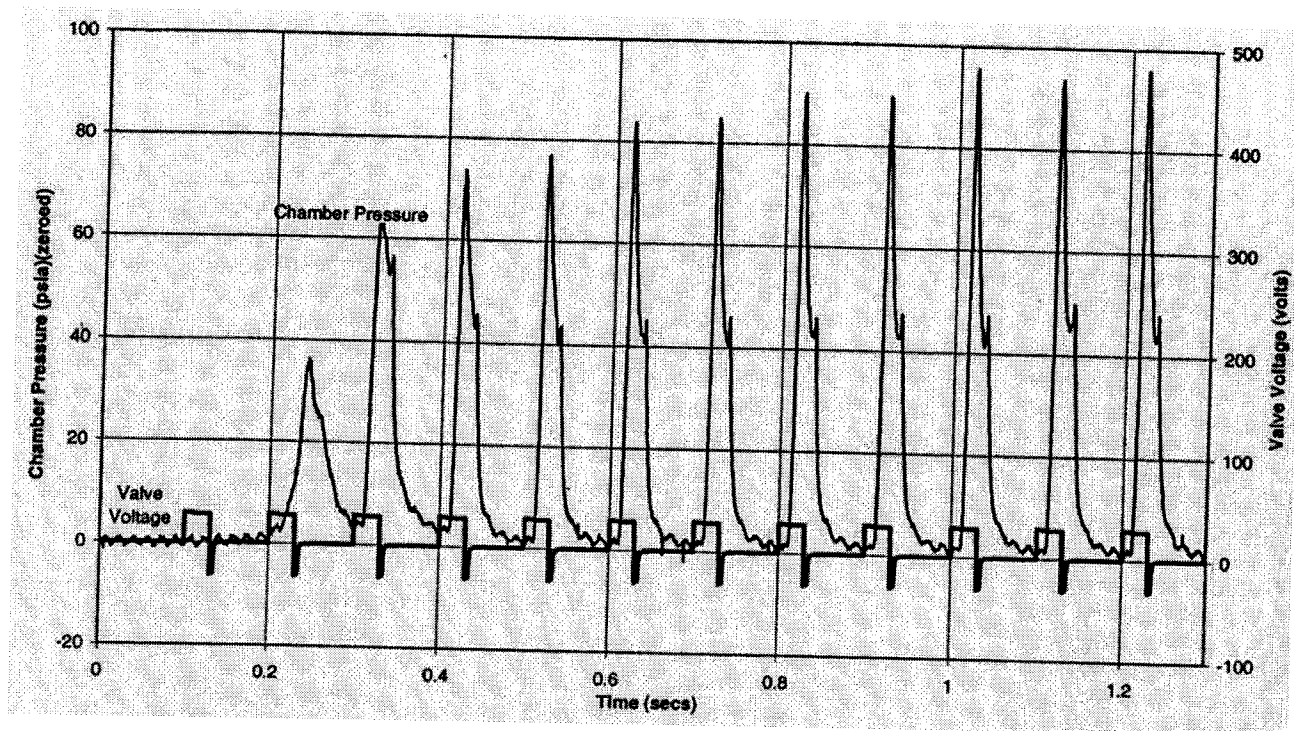


Figure 12 Test Point 12 (30% DC, -20C) Pulses 1 through 12

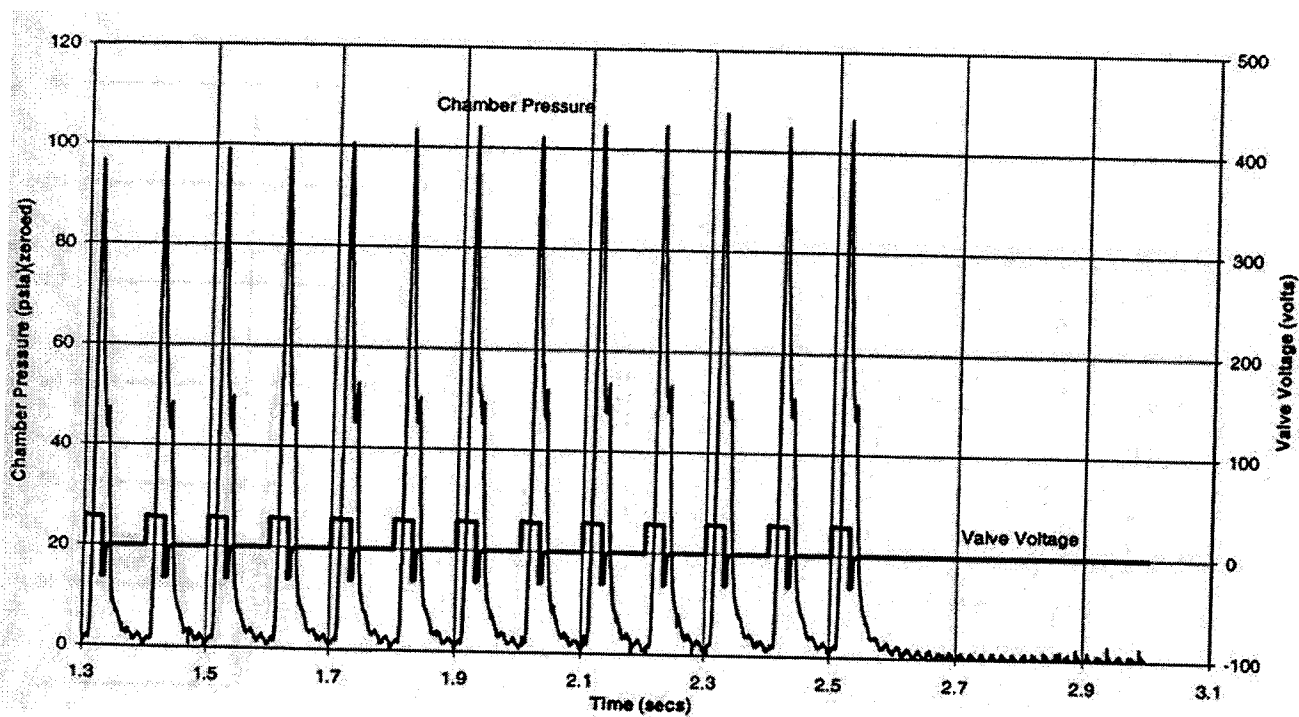


Figure 13 Test Point 12 (30% DC, -20C) Pulses 13 through 25

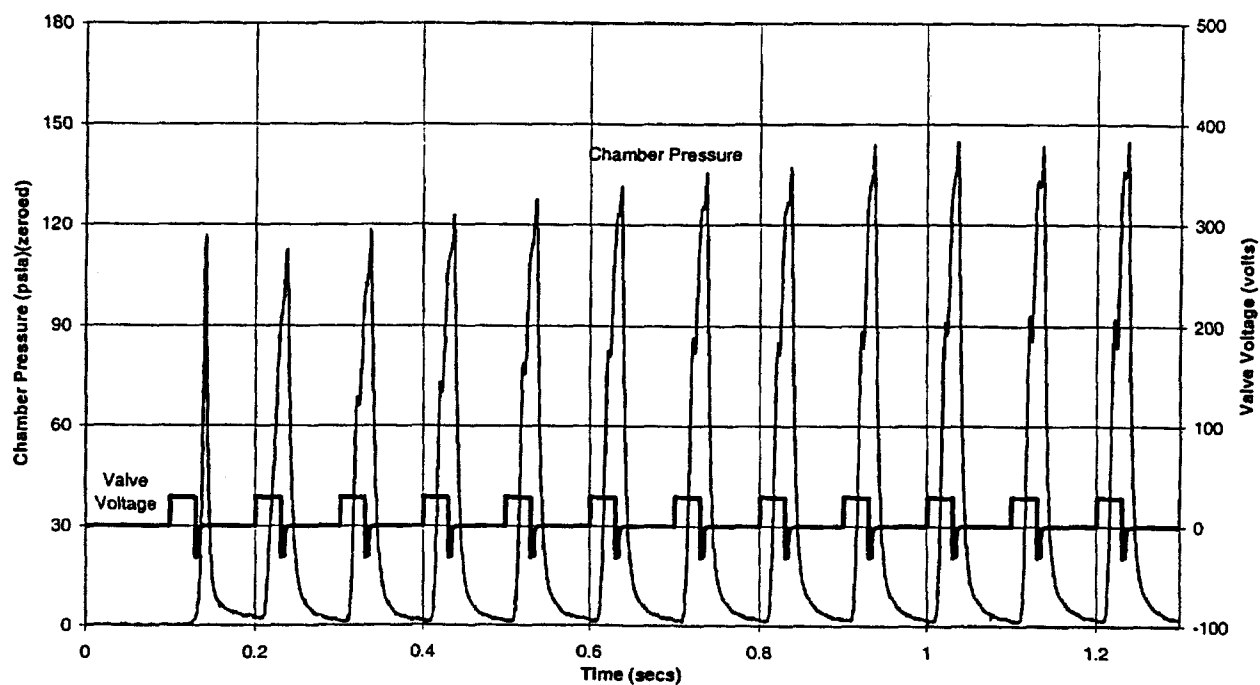


Figure 14 Test Point 18 (30% DC, 12C) Pulses 1 through 12

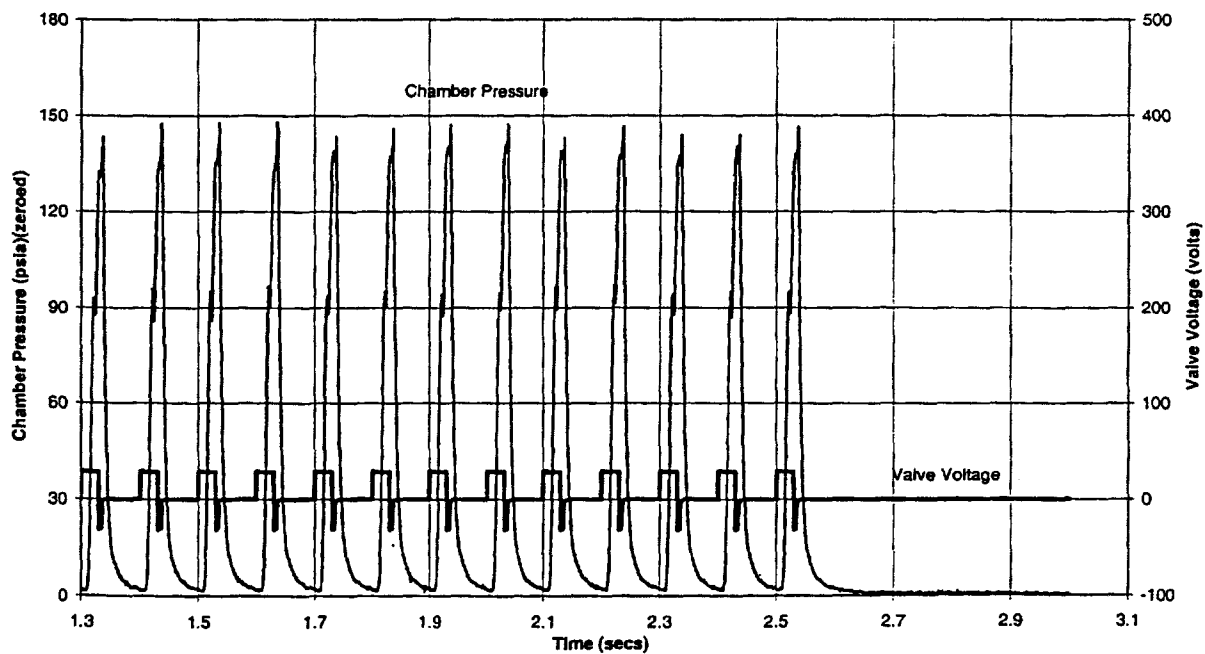


Figure 15 Test Point 18 (30% DC, 12C) Pulses 13 through 25

### **Conclusions**

Cold validation testing verified the Mar Polar Lander descent thruster cold start "qualification by similarity" assessment. Specifically, testing demonstrated that the MR-107N thruster could successfully start with catalyst bed temperatures predicted to be between 0° C and minus 28° C.

Testing conducted by GD verified that the thruster could indeed be started with the catalyst bed temperature as low as minus 28° C. Seven starts were successfully completed with the catalyst bed temperature between minus 30° C and 0° C and the fuel temperature from 7° C and 14° C.

This test program also developed an extended valve preheat sequence that increased the nominal catalyst bed temperature to 12.8° C providing significant margin above the demonstrated cold start capability. This preheat approach was implemented for the MPL descent and landing.

At temperatures below the freezing point of hydrazine, there can be significant response delays or the first one or two pulses may have no measurable impulse. In addition, there will be increased catalyst attrition which may affect performance and thruster life. Future programs with extreme cold start requirements should assure that this first pulse

variability and initial low performance (start transient) are acceptable for their mission requirements. Most missions should not use this capability for nominal operation of the spacecraft. Special situations such as emergency operation or very short missions (Several starts, limited total pulses and limited propellant throughput) could be acceptable but must be given careful scrutiny on a case by case basis.

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